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AUTOMATED HELIUM GAS METERING SYSTEM

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Abstract

This report describes the design and operation of a computerized high pressure gas metering system that is successfully testing vessels at the Lawrence Livermore National Laboratory. This system can precisely control pressure up to 16,000 psi at rates of 25 to 5000 psi/min with a 500 cc vessel. Digital feedback control and estimation techniques are used to track a pre-defined pressure profile that can include positive, negative, and zero rates. Thirty-eight instrumentation channels are available for monitoring a test run and data acquisition. During the experiment, up to eight preselected curves can be plotted and numerical data from all transducers are displayed with physical units in real time. A diagram dynamically shows the status of the system. Finally after a test, plot routines aid the experimenter to analyze the acquired data.

INTRODUCTION

The personnel of the High Pressure Laboratory have successfully built an automated gas metering and data acquisition system for pressure testing up to 16,000 psi[1]. This unique capability is valuable for tests requiring acoustic emission or holographic data where precise control of pressure or pressurization rate is needed. The micro-computer controller allows a wide range of volumes and rates saving manpower previously to set up a ramping test with manual cut and try methods. In addition to controlling the test, the computer provides a data acquisition service for measurements other than just system pressure. The data acquisition software also shortens the time needed to setup and calibrate these transducer data channels.

The control software compensates for the different vessel volumes that may be tested. Metering system performance varies with actual volume, rate and maximum pressures in a given test, but typically a 500 cc vessel can be pressurized with helium up to 16,000 psi at 25 to 5000 psi/min. The vessel pressure will follow a predefined profile that can consist of several different rates. Positive, negative, and zero pressurization rates can be accommodated. In addition, the system can be preset to minimize the pressure or flow variations for the given test requirements.

[1] A prototype system was developed at LLNL. (Tripp, 1980)

The data acquisition service can accommodate up to 26 high level and 12 low level transducer measurements associated with the test. All high level channels can be scanned 60 times/sec and all low level channels can be scanned once each second. Approximately 200,000 total measurements can be taken and stored on a floppy disk during each test.

The data acquisition software also contains routines that aid the calibration of the transducer channels. Channels are calibrated in several ways such as specification of scale factors or direct stimulus of the transducer. This calibration data is also stored on the data disk so that after the test, the measurements can be converted to engineering units and plotted in a variety of ways.

During the test run, up to eight preselected signals can be displayed graphically to monitor the course of the experiment. The numerical data from all channels can be displayed in engineering units while the test is in progress. The real time software allows the operator to monitor the system status via a diagram showing valve positions, pressurized lines and other system variables. The operator can also re-direct the course of a test with keyboard commands. The options include aborting the test, venting the vessel, suspending profile execution, and defining a new profile segment.

OPERATION

Figure 1 shows the relationship of all the high pressure components. All valve positioning and sequencing is controlled by the micro-computer. The necessary peripherals and interfaces are shown in the interconnection diagram of Figure 2. The operator interacts with the system by means of the keyboard and CRT display on the graphics terminal.

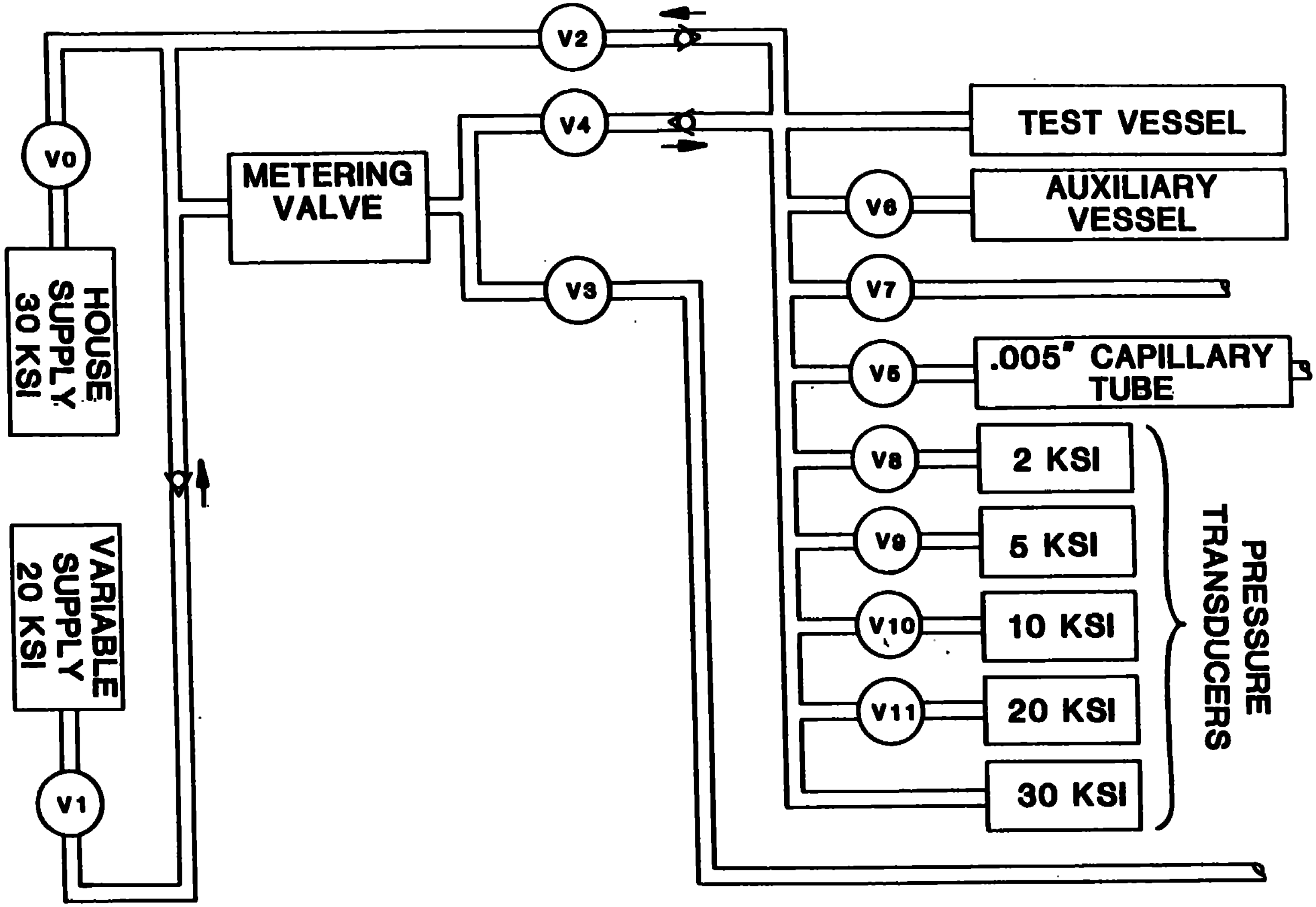


FIG. 1. SCHEMATIC FLOW DIAGRAM

GAS METERING SYSTEM INTERCONNECTION DIAGRAM

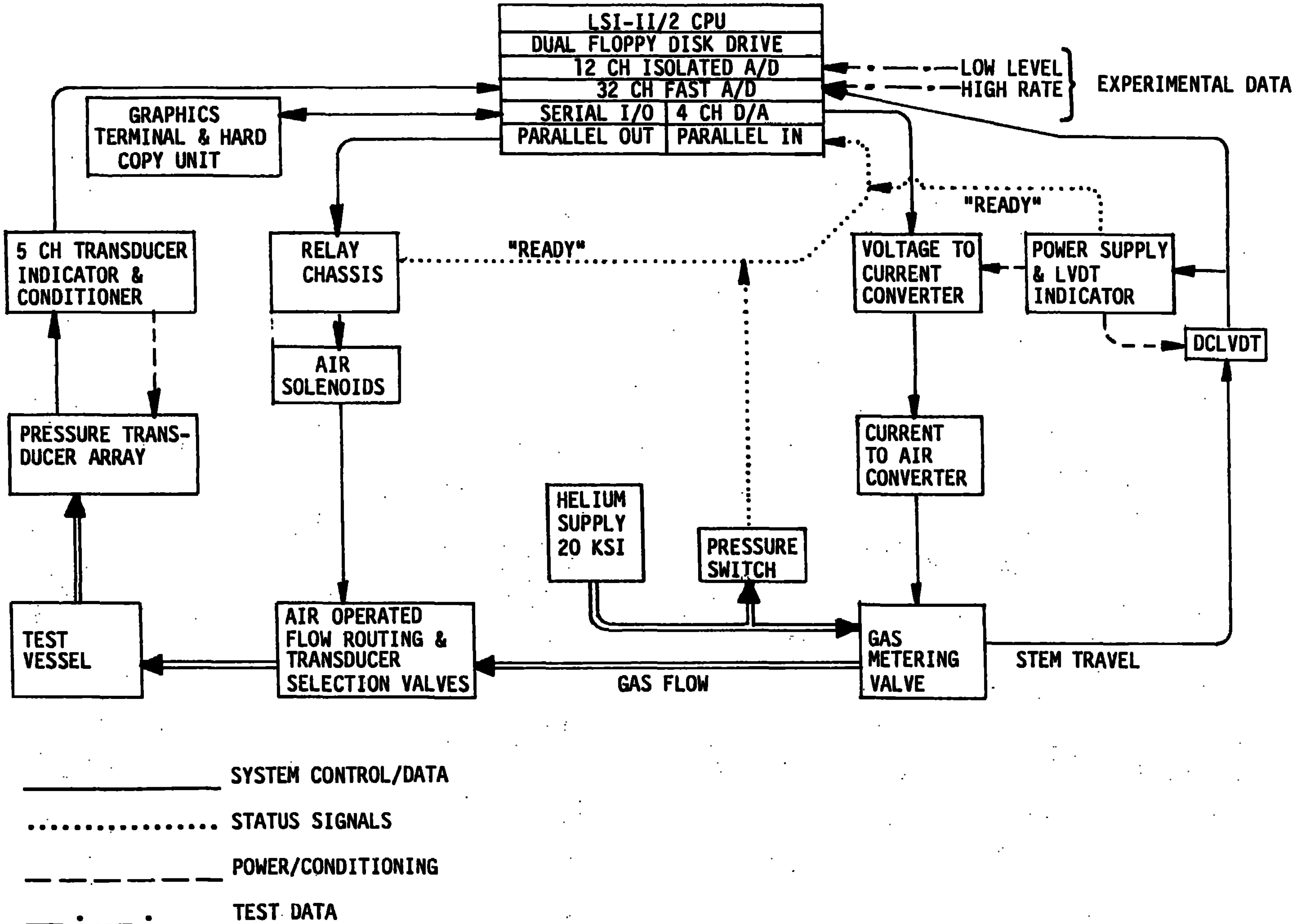


Figure 2
Gas Metering System Interconnection Diagram

The software and hardware that control helium flow in the system have two main functions. One is to position all on-off valves for flow routing and transducer selection. The other is to control the pressurization rate by positioning the metering valve. The software automatically selects on-off valves to actuate according to the desired pressure profile. All the on-off valves are normally closed except valve 7 which is a normally open valve used to quickly vent the test vessel and the system. A power failure would thus automatically cause the vessel to be vented. Each on-off valve is air operated by a 90 psi source against a diaphram. The actuating pressure is switched by a bank of solenoids as commanded by the computer.

Only one of the supply valves, V0 or V1, will be used for a test. Valve V0 connects to the 30 Ksi house supply and would be used if the maximum pressure exceeds 16 Ksi. Valve V1 connects to a manually filled 4-liter vessel that can be used as a variable pressure supply up to 20 Ksi.

Valves V2, V3 and V4 are used to keep the flow through metering valve in the same direction during up and down ramps. Valves V0 or V1, and V4 are opened for a fill while V2 and V3 are closed. These positions are reversed for controlled venting. The check valves in line with V2 and V4 prevent gas flow around the metering valve while the valves are changing position.

Valve V5 vents the system to atmosphere through a .005 inch diameter capillary tube. This is used for flow characterization of the metering valve. Valve V5 is not used during a test run.

Since the metering valve leakage and resolution will not allow the very low flows for small test vessels, a 100 cc auxiliary volume can be added to the system by opening valve V6. The software opens valve V6 whenever the specified test volume is less than 100 cc.

The test vessel can be vented quickly when valve V7 is opened. The operator can also cause a vent by depressing the "vent" button on the solenoid control chassis or the "vent" or "abort" key on the terminal keyboard. Normally, a vent will occur automatically at the end of a specified pressure profile.

Valves V8 through V11 select the pressure transducer to be used throughout the test. The software will determine the lowest range transducer exceeding the maximum profile pressure and actuate the correct valve. That transducer will then provide the data that is stored for the experimenter and used for system pressure control.

The pressure control software contains an equation that reflects the helium flow versus metering valve stem displacement. The coefficients of the flow equation are determined experimentally with the aid of a separate calibration program.

The required flow is determined from the desired pressurization rate and test volume. Then the flow equation is used to calculate the initial metering valve stem position. When the system is running, a sample of the system pressure transducer is used at two second intervals to make filtered estimates of the pressure and flow errors. Kalman filtering techniques are used to form these estimates. The stem position command is then increased or decreased to reduce the flow error. The operator can specify the fraction of pressure error that will be removed over the next interval. On some types of tests (e.g. those with acoustic emission instrumentation), pressure errors are not as important as a constant flow. In these cases this variable could be set to zero to remove the flow variations due to pressure corrections.

Once the desired metering valve stem displacement has been computed, a digital-to-analog (D/A) converter outputs a proportional voltage which drives the pneumatic positioner on the metering valve. Since increasing downstream helium pressure forces the valve stem to move, it is necessary to measure the stem position and make corrections to the command displacement.

A linear variable differential transformer (LVDT) is used to measure the stem travel of zero to 0.020 inch. The software, by means of the A/D converter, samples this signal every 0.1 sec and increases or decreases the voltage on the D/A converter to correct for positional errors.

The stem position feeds back a proportional plus integral controller with parameters determined with the aid of a separate diagnostic program. The metering valve (a commercial model with the smallest available trim set) has a tapered (1 degree included angle), cylindrical (.1 inch diameter) plug in a matching seat. The small size of the trim set and the need to almost close off flow require that the system be kept clean and that filters be placed before the metering valve.

The actuator is an air operated piston working through a lever whose ratio is adjustable. For the gas metering system, the ratio is adjusted to give the plug a maximum stem travel of .020 inch. The positioning of the piston is accomplished by an internal pneumatic feedback loop which controls the displacement of the piston.

The metering valve was modified to improve its input-output characteristic such that it could be used in a closed feedback loop. The modifications included:

Decreasing the leak rate by carefully lapping the valve plug to the valve seat.

Extending the controllable range of flow as low as possible by stiffening the overall structure to minimize distortions as the actuator forces change.

Reducing hysteresis in the actuator by replacing the 6-inch diameter O-rings with loose fitting Teflon spring energized seals and by polishing the bore of the cylinder.

Eliminating the "flat spots" that occur after cycling the valve a few hundred times by remanufacturing the guide bushings with higher strength material.

The computer has two boards installed for data acquision. One is a 32 channel, high level, analog-to-digital converter (fast A/D) capable of sampling data at rates up to 20,000 samples/second. This unit can be used to acquire data from rapidly changing signals in the range of + 5 Volts with a resolution of 2.5 mV. The first 6 channels are dedicated to signals required for system control (metering valve stem position and the 30K, 20K, 10K, 5K, and 2 Ksi pressure transducers in that order). The remaining channels can be used for other experimental data.

The other board is a 12 channel isolated analog-to-digital converter (slow A/D) with software programmable gains that is dedicated to the acquisition of low-level experimental data. Each channel has an individually programmable gain (500, 100, 10, 1) to accommodate signals of 20 mV, 100mV, 1.0V, and 10.0V. The unit samples at a slow rate of 40 samples/second when all gains are the same. The resolution is .05%.

The data acquisition software is used in three phases of a typical pressure test. They are pre-test channel calibration, acquisition and storage during the test, and post-test plotting of the data. The pre-test calibration program allows the operator to specify transducer dependent information for each channel. This includes transducer type, serial number, engineering units, gain for the slow A/D, scale factor and offset. If it is possible to provide two reference inputs at the transducer, the software will provide an end-to-end channel calibration by computing the offset and scale factor for the transducer and A/D channel combination. This routine also provides a tabular listing of the A/D readings for channel verification before a test begins.

The data acquisition software must run concurrently with the control software when the test is in progress. At this time, the primary acquisition tasks are to sequentially read all channels in use on both A/D converters and store the data on the floppy disk. This sampling rate is either specified by the operator or selected by the system software to be the minimum of system throughput rate or the rate that will use 80% of the disk storage capacity for all the test data. The maximum system throughput depends on which A/D converters are being used and the real time options that are in effect. The disk drive unit has a maximum storage rate of 8,800 data points/second.

After the test has been completed, the data can be recalled from the disk and plotted in a variety of ways. Either linear or logarithmic axes can be used to get graphs of any channel versus time or any other channel. It's also possible to enlarge a section of graph for more detail. Permanent records of the plots can be provided by a hard copy unit which reproduces the information shown on the CRT screen.

The interface between the operator and the metering system is a "smart" CRT terminal with features that include vector graphics, user definable character sets, and buffered communications between the keyboard and computer. The terminal has extensive display and graphics memories that reduce the CPU-terminal communications overhead during a test.

Most of the operator interface software uses multi-level menus to guide the setup of a test run. Figure 3 illustrates two of these menus. In operation, the selection of item 1 in menu 3a leads to menu 3b. Selection of item 4 in menu 3b leads to the appropriate applications software. Selecting "HELP" on any menu will provide the operator with a more detailed explanation of the options on that menu. Once the operator has entered all the necessary information for a test, he is allowed to select the "Initialize Terminal To Start Test" item on the last menu. After verifying the items on a checklist of manual operations (e.g., secure cell), he is presented with the display shown in Figure 4. This mimic diagram dynamically shows the status of the system during a test. Pressurized lines and actuated valves are shown with filled-in symbols.

The system pressure, elapsed time, and metering valve stem position are also displayed. The lower portion of Figure 4 is a menu that shows the functions of the programmable keys directly below the screen. Two of the keys will recall displays that show more information on the progress of the test.

Figure 6 is the result of pressing the "VIEW PLOT" key. Up to eight preselected data channels can be shown on this real time plot. Only the first plotted channel (normally system pressure) is scaled by the left hand coordinate. The other channels can be converted to engineering units by using the scale factors at the bottom of Figure 6 on the right coordinate. Whenever the system pressure is plotted, the intended profile is shown with dotted lines. This particular run is explained in the results section.

The operator can also call up a tabular listing (in engineering units) of all active A/D channels by using the "VIEW TABLE" key. This table is updated as new data is acquired. The remaining key functions shown in Figure 4 allow the operator to control the course of the test. For example, the "VENT END" key will depressurize the test vessel and system and terminate the data acquisition before the profile is completed. If the test ends with an automatic or manual vent, then the program determines that all lines and vessels are at atmospheric pressure and presents a post-test checklist to the operator before terminating.

USER'S TRANSDUCERS

1. CALIBRATE USER'S TRANSDUCERS ON FAST A/D
2. CALIBRATE USER'S TRANSDUCERS ON SLOW A/D
3. DISPLAY USER'S TRANSDUCERS ON FAST A/D
4. DISPLAY USER'S TRANSDUCERS ON SLOW A/D
5. CURRENT VALVES OF USER'S TRANSDUCERS ON FAST A/D
6. CURRENT VALVES OF USER'S TRANSDUCERS ON SLOW A/D
7. HELP
8. RETURN TO MAIN MENU

PRESS SPACE BAR TO CHANGE OPTION
PRESS RETURN TO SELECT OPTION

(A)

CALIBRATE USER'S TRANSDUCER ON FAST A/D

1. CHANNEL NUMBER (6-31)
2. DESCRIPTION OF TRANSDUCER (8 CHARS MAX)
3. ENGINEERING UNITS (4 CHARS MAX)
4. TYPE OF CALIBRATION
   1 SHUNT CALIBRATION
   2 KNOWN INPUTS
   3 MANUAL ENTRY

5. HELP
6. RETURN TO USER'S TRANSDUCER MENU

PRESS SPACE BAR TO CHANGE OPTION
PRESS RETURN TO ENTER OPTION

(B)

Figure 3 Typical Menus Used to Define a Test

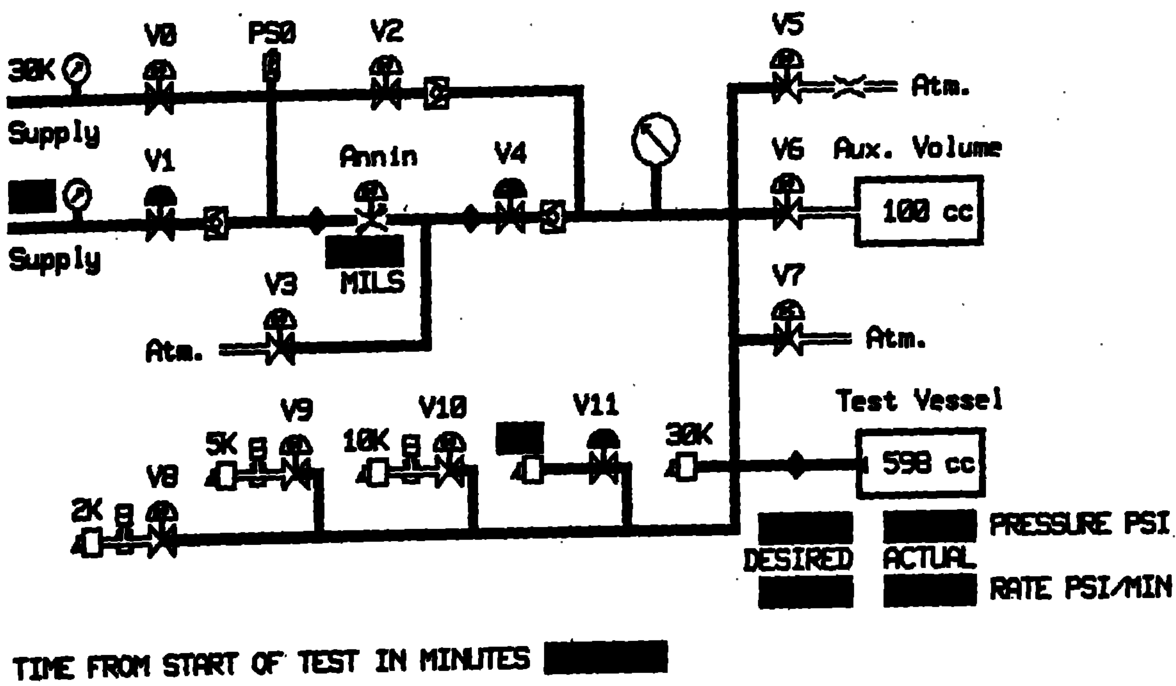


Figure 4

System Status Diagram as
Shown During a Test

RESULTS

The typical performance of the Gas Metering System can be illustrated by observing two experimental runs.

Run #1

Run No. 1 involves measuring circumferential strain on a 36.49 in^3 spherical vessel as it is pressurized initially at 2000 psi/min and then at 500 psi/min. At the maximum pressure the vessel is valved off in a "hard hold" state in which no control over pressure is exercised and is then kept at constant maximum pressure in a "normal hold" state. The vessel is then depressurized at 1000 psi/min. The desired pressure profile is shown in Figure 5.

The three real-time plots of Figure 6 show actual system performance. These data are plotted point by point as each measurement is taken. Observing curve #2 of the vessel pressure versus time, the system does well in following the desired pressure profile along both slopes of increasing pressure and during the normal hold. Note that during the hard hold when the vessel is valved off, the pressure in the vessel decreases due to the cooling of the helium. This phenomenon is more clearly illustrated in the blowup of Figure 7. This expanded plot is an example of one of the many options in obtaining post experimental graphs. The sag in pressure can be eliminated by using a normal hold which allows the flow of additional helium into the vessel. Referring back to Figure 6, note also that the actual pressure profile (curve #2) departs from the desired profile during depressurization of the vessel at the point where the metering valve (curve #1) is fully open and the vessel pressure is too low for the required flow. Curve #1 shows the valve stem position versus time and curves #3 - #5 are strain versus time.

The ability to obtain plots of any measured variable versus any other variable is illustrated in Figure 8. Here the circumferential strain of the vessel is plotted against vessel pressure.

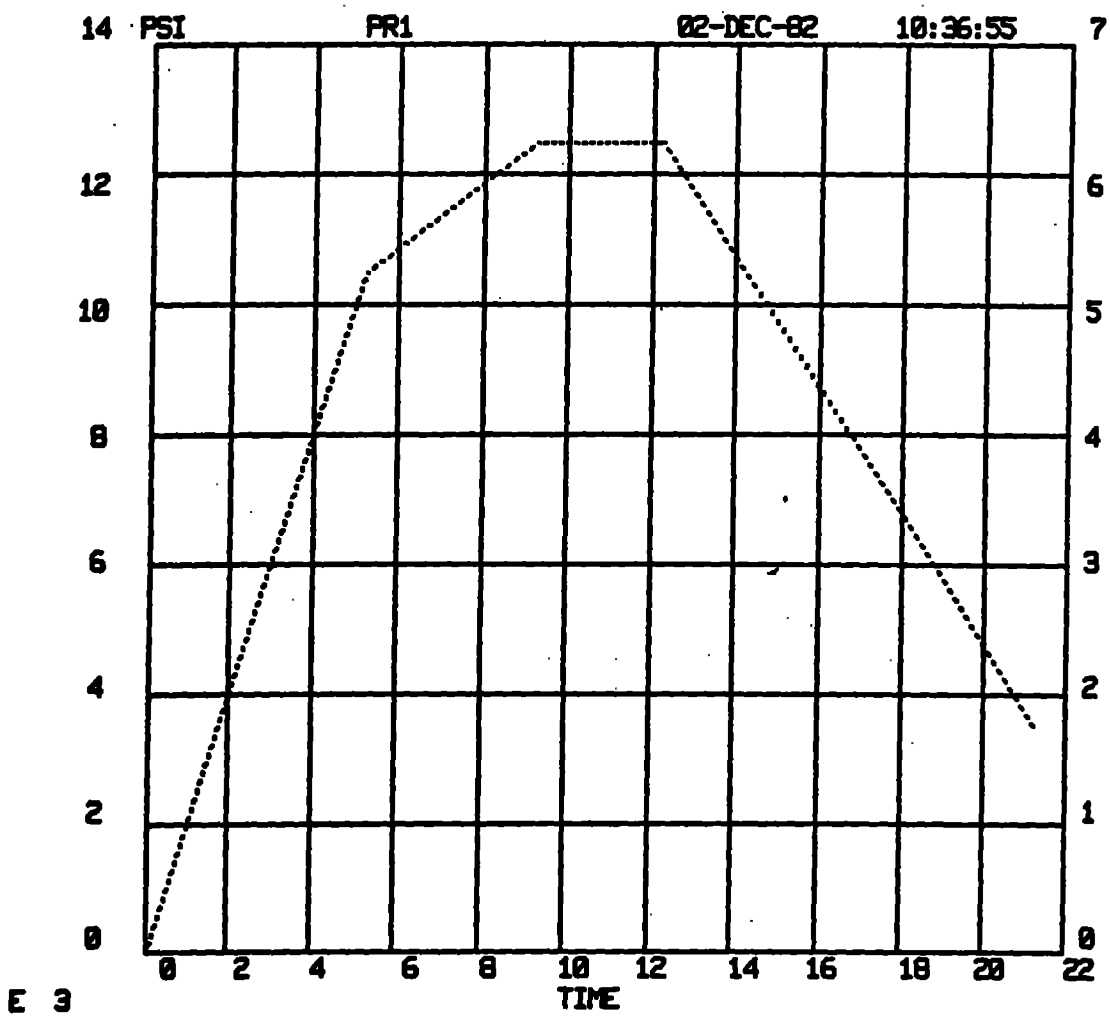
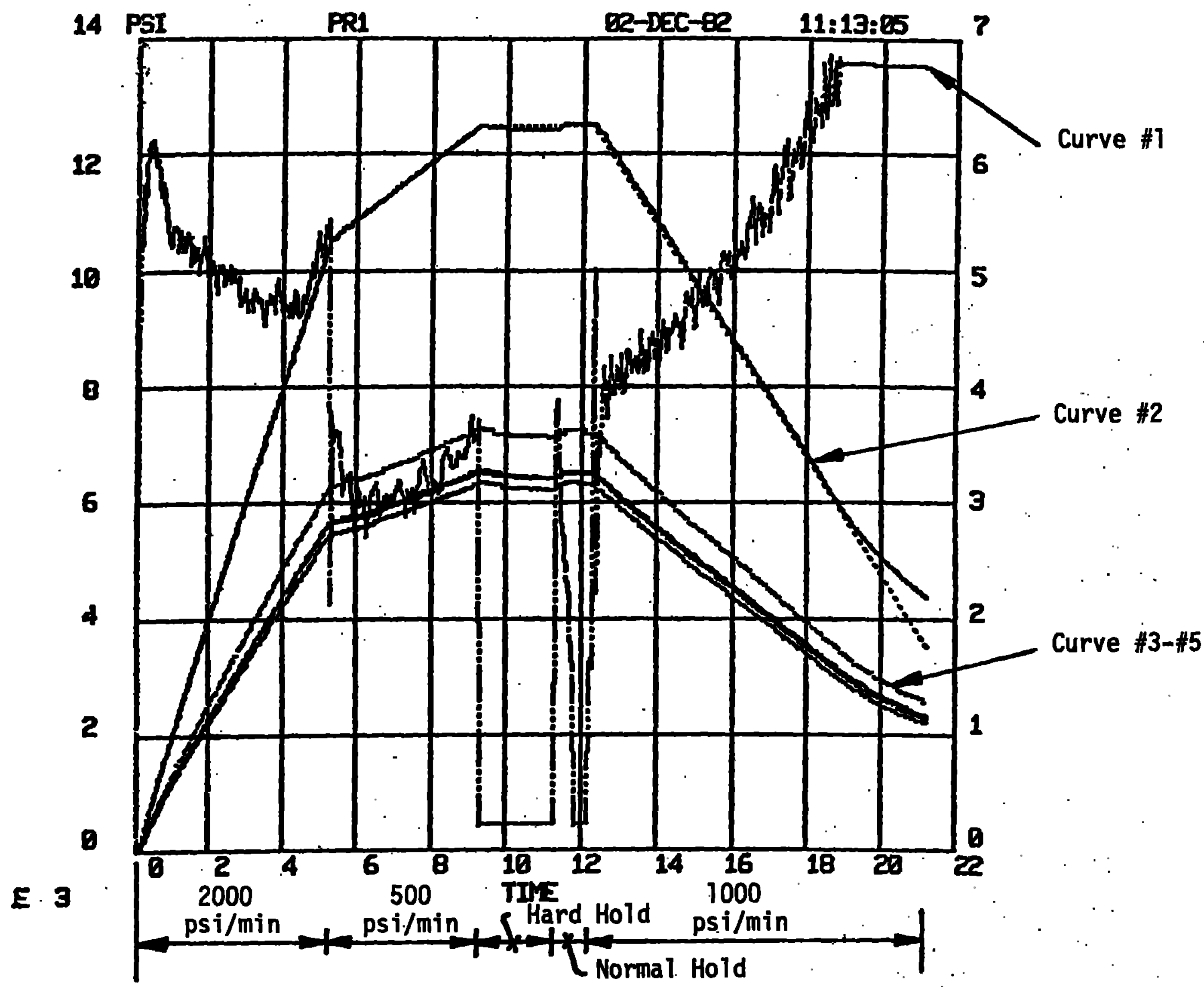


Figure 5

Desired Pressure Profile



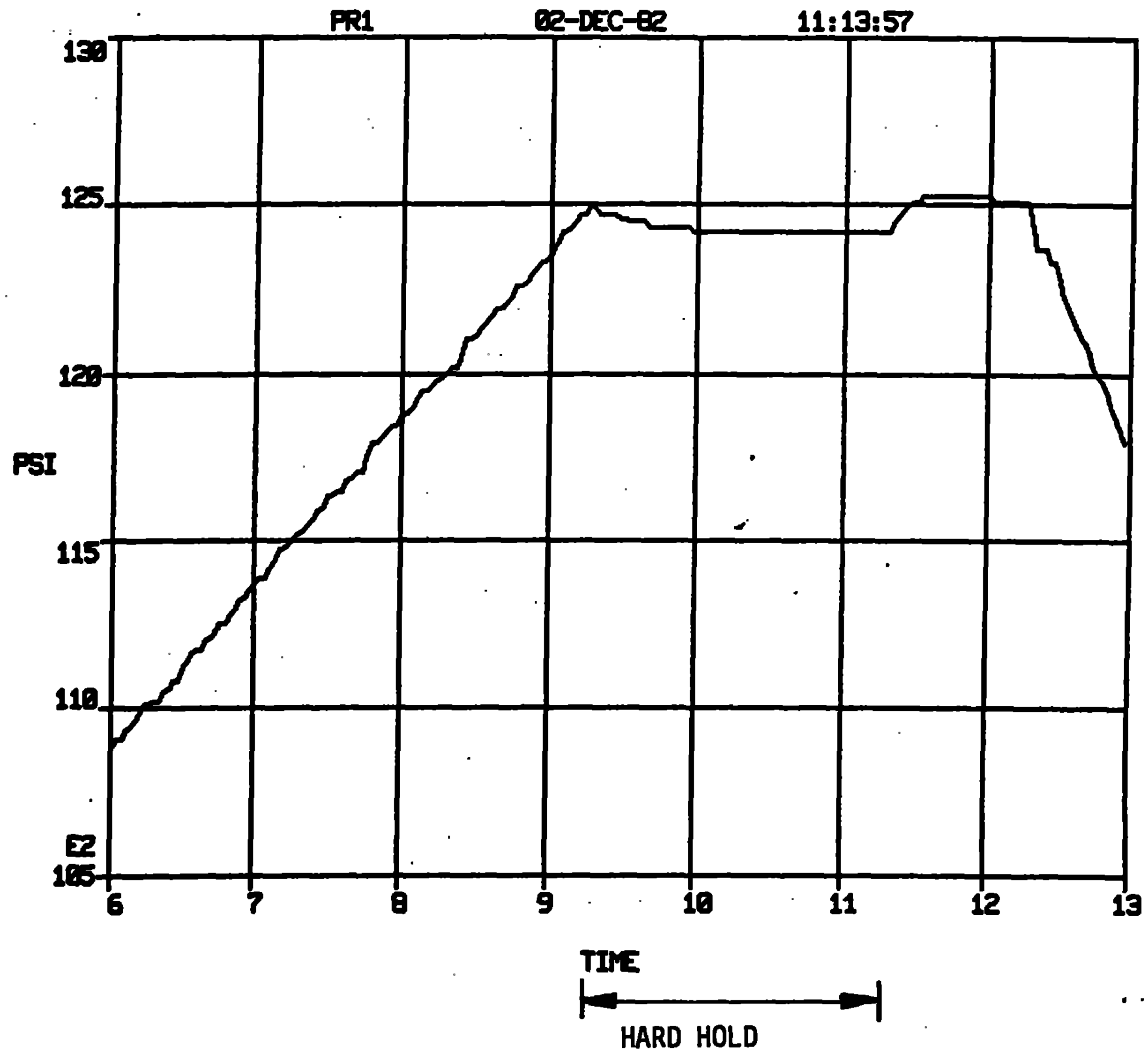
		VERTICAL AXIS			HORIZONTAL AXIS			
PLOT	TYPE	MINIMUM	MAXIMUM	UNIT	TYPE	MINIMUM	MAXIMUM	UNIT
1	P	0.0000	0.1400E+05	PSI	T	0.0000	22.00	TIME
2	S 0	0.0000	750.0	MI/I	T	0.0000	22.00	TIME
3	S 1	0.0000	750.0	MI/I	T	0.0000	22.00	TIME
4	S 2	0.0000	750.0	MI/I	T	0.0000	22.00	TIME
5	S 3	0.0000	750.0	MI/I	T	0.0000	22.00	TIME
6	L	0.0000	20.00	MILS	T	0.0000	22.00	TIME

T=TIME IN MINUTES
P=SYSTEM'S PRESSURE IN PSIG
L=LVDT IN MILS
F=USER'S FAST A/D CHANNEL
S=USER'S SLOW A/D CHANNEL

Figure 6

Typical Data Plotted in Real-Time for Run #1

Curve #1 - Displacement of metering valve versus time
Curve #2 - Pressure versus time
Curves #3-#5 - Strain versus time



NAME OF EXPERIMENTER K. BLAEDEL
NAME OF OPERATOR MICHAEL

INNER DIAMETER OF TUBE IN MILS 62.0
LENGTH OF TUBE IN INCHES 36.0
VOLUME OF VESSEL IN CC 598.

HORIZONTAL AXIS
TIME IN MINUTES

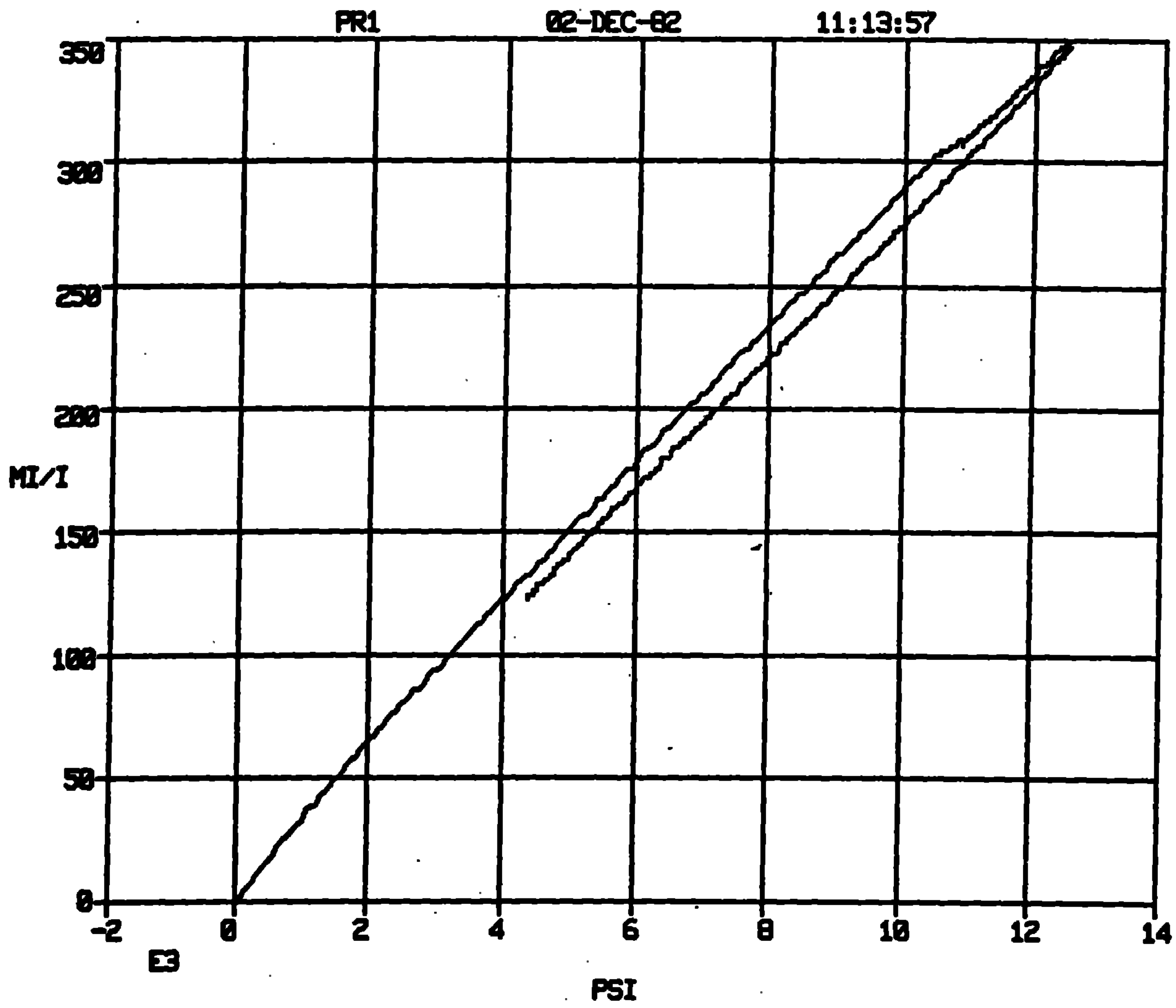
VERTICAL AXIS
SYSTEM'S PRESSURE IN PSIG

Figure 7

Expanded Plot of Hard Hold for Run #1
Pressure versus Time

RUN #2

Referring back to Figure 6, curve #2 of valve stem position versus time looks quite noisy. A large portion of the observed noise is the necessary valve stem movement to change the flow to correct pressure errors. If the instrumentation on the test vessel were particularly sensitive to the rate of flow into the vessel, then these flow variations would be quite undesirable. For such a test, involving for example acoustic emissions, the desire is for constant flow and to some extent a compromise is struck by allowing a slight departure from the desired pressure profile. This is accomplished, as discussed earlier, by reducing the amount of presssure error correction in each sample and control interval. Comparing to Run #1, Run #2 of Figure 9 shows a smoother plot of valve stem position versus time (curve #2) and the consequent deviation from the desired pressure profile (curve #1). Run #2 is conducted identically to Run #1 except 0% of the pressure error is corrected at each sample, reduced from 30% in Run #1. In both runs, however, the stem position is changed to correct for the estimated flow errors of the metering valve.



NAME OF EXPERIMENTER K. BLAEDEL
NAME OF OPERATOR MICHAEL

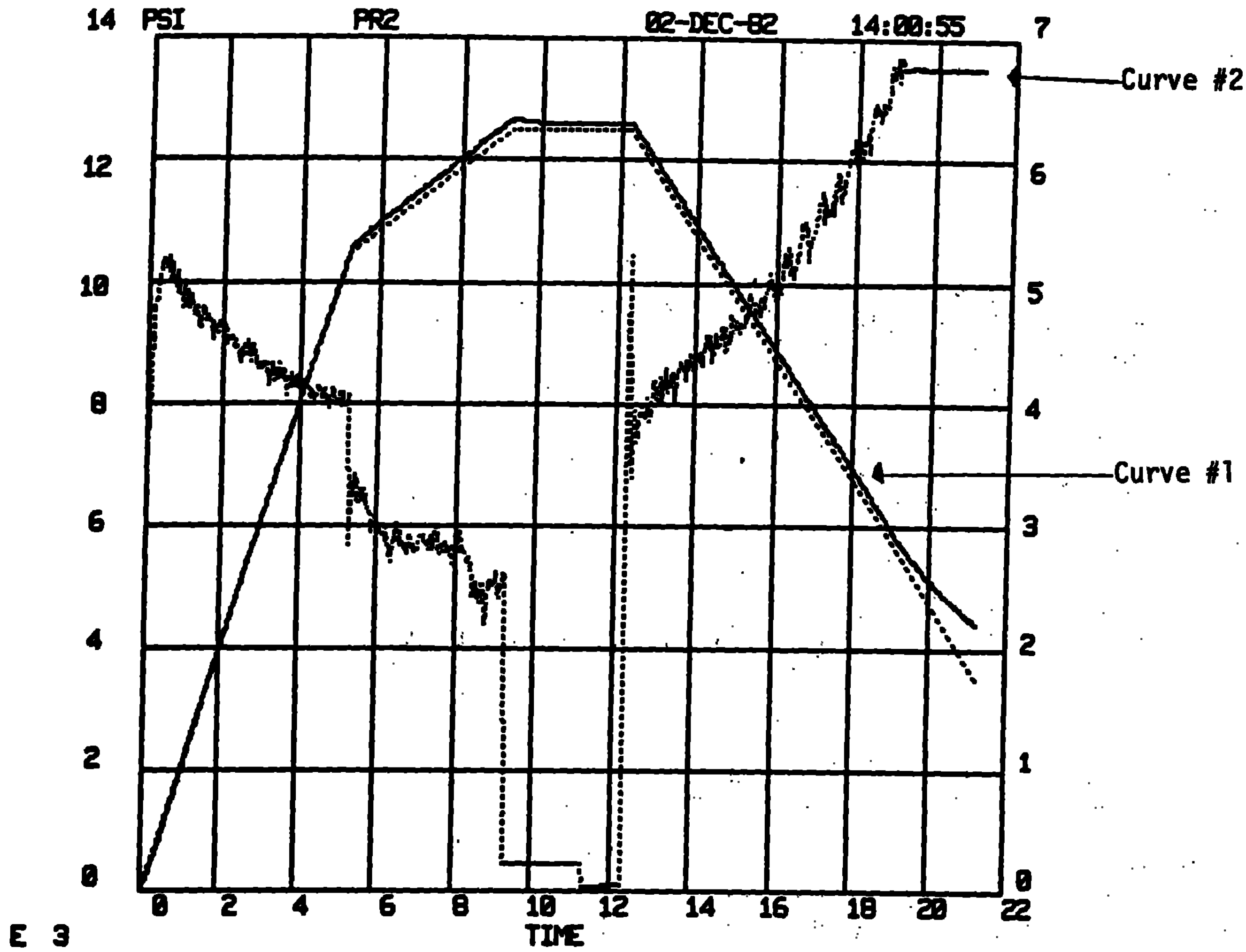
INNER DIAMETER OF TUBE IN MILS 62.0
LENGTH OF TUBE IN INCHES 36.0
VOLUME OF VESSEL IN CC 598.

HORIZONTAL AXIS
SYSTEM'S PRESSURE IN PSIG

VERTICAL AXIS
SLOW A/D CHANNEL # 2 IN MI/I

Figure 8

Typical Post Experimental Plot
Strain in Microinches/Inch versus Pressure in PSI



		VERTICAL AXIS				HORIZONTAL AXIS		
PLOT	TYPE	MINIMUM	MAXIMUM	UNIT	TYPE	MINIMUM	MAXIMUM	UNIT
1	P	0.0000	0.1400E+05	PSI	T	0.0000	22.00	TIME
2	L	0.0000	20.00	MILS	T	0.0000	22.00	TIME

T=TIME IN MINUTES
P=SYSTEM'S PRESSURE IN PSIG
L=LVDT IN MILS
F=USER'S FAST A/D CHANNEL
S=USER'S SLOW A/D CHANNEL

Figure 9

Real Time Plots for Run #2

Curve #1 - Pressure versus Time
Curve #2 - Displacement of Metering Valve versus Time

Conclusion

A computer can be used to automate the process of pressure vessel testing. More precise control of pressures and flows can be attained than with manual methods. A wide range of test conditions can be accommodated with the same hardware setup. Once the input parameters and pressure profile have been specified, the test can be carried out without operator intervention. The data acquisition service is more convenient than previously used analog methods. The digitized data can be displayed graphically in real time to monitor the progress of the test. This data is also stored on a floppy disk for post-test processing and plotting.

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